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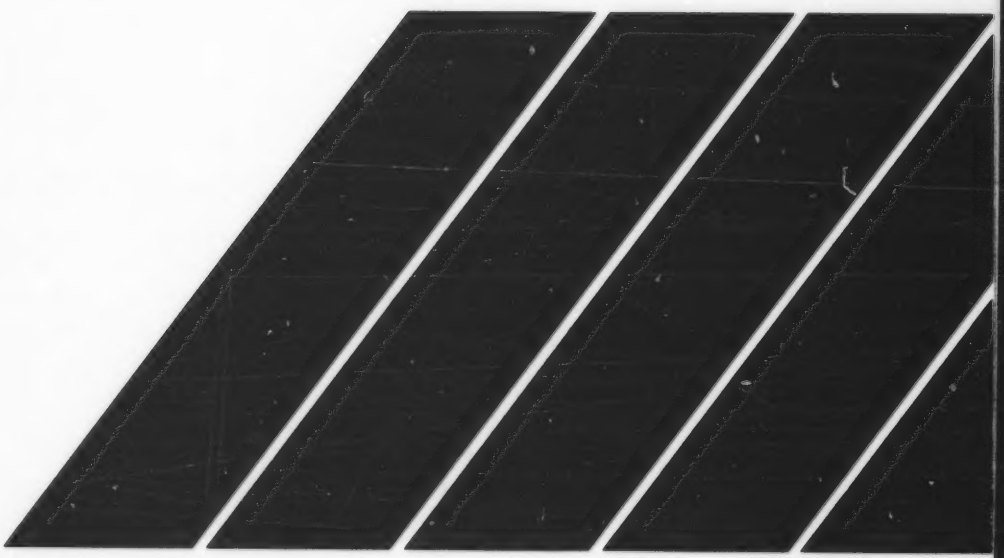
PHOTOVOLTAIC SYSTEMS AND WIND TURBINES: LIGHTNING PROTECTION REVIEW



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PHOTOVOLTAIC SYSTEMS AND WIND TURBINES: LIGHTNING PROTECTION REVIEW

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TABLE OF CONTENTS

PAGE

ABSTRACT iv

1.0 INTRODUCTION 1

2.0 LIGHTNING PHYSICS 2
2.1 Characteristics 2
2.2 Probability of Strike 3
2.3 Thunderstorm Days 3

3.0 LIGHTNING PROTECTION METHODS 5
3.1 Lightning Rod 5
3.1.1 Lightning Rod Protective Zone 5
3.2 Overhead Ground Wire 6
3.3 Hardening against lightning 6
3.4 Pre-emptive strikes 6
3.5 The Dissipation Array System (DAS) 6
3.6 Radioactive Head, - HELITA 7

4.0 LIGHTNING PROTECTION OF WIND TURBINES AND PHOTOVOLTAICS 8
4.1 Rationale for Lightning Accommodation System 8
4.2 Protection to a Horizontal Axis Wind Turbine (HAWT) 8
4.2.1 Electrical Power System Protection 8
4.2.2 Blades and Mechanical Components Protection 9
4.2.3 Electronics Protection 10
4.2.4 Grounding, Shielding and Bonding Protection 12
4.2.4.1 Grounding Protection 12
4.2.4.2 Shielding and Bonding 13
4.3 Vertical Axis Wind Turbines (VAWTs) 14
4.3.1 Lightning Protection of VAWTs 14
4.3.1.1 Protection of the Machine 14
4.3.1.2 Protection of the instrumentation and controls 16
4.3.1.3 Ground gradient protection 17
4.4 Lightning Protection of Photovoltaic Power Systems 17
4.4.1 General 17
4.4.2 Lightning Threat 18
4.4.3 Coupling considerations 18
4.4.4 Damage Thresholds 18

5.0 CONCLUSIONS AND RECOMMENDATIONS 20

6.0 LIST OF FIGURES 23

7.0 REFERENCES 24

ABSTRACT

This study reviews lightning protection to photovoltaic array systems and to wind turbines as electricity generators. It covers both horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). The thrust of the study is on photovoltaic systems and medium and large wind turbines, ranging from 100 kW to multi-megawatts. The study concludes that although absolute lightning protection is not achievable, there is currently sufficient knowledge about lightning and its behaviour under diverse conditions due to significant scientific and engineering advances achieved during the last 10 years to enable designers to provide satisfactory protection to wind turbines and photovoltaic power plants and to operating personnel.

RÉSUMÉ

Les auteurs de cette étude examinent les moyens de protéger de la foudre les générateurs photovoltaïques et les éoliennes servant à la production d'électricité. L'étude englobe tant les éoliennes à axe horizontal que les éoliennes à axe vertical. Elle met l'accent sur la photovoltaïque et les éoliennes d'importance moyenne et élevée dont la capacité varie de 100 kilowatts à plusieurs mégawatts. Les auteurs de l'étude en sont venus à la conclusion que, bien qu'il soit impossible de protéger pleinement ces installations contre la foudre, les connaissances acquises à l'égard de ce phénomène et de ses manifestations dans diverses conditions grâce aux importants progrès scientifiques et techniques réalisés au cours de la décennie sont suffisantes pour permettre aux concepteurs de fournir une protection satisfaisante aux éoliennes, aux centrales électriques photovoltaïques et à leur personnel.

PHOTOVOLTAIC SYSTEMS AND WIND TURBINES LIGHTNING PROTECTION REVIEW

1.0 INTRODUCTION

The chances of lightning damage to wind turbines is increasing as these machines become larger and more numerous on individual sites. Windfarms now exist that have well over 100 wind turbines. Turbines now in operation have heights exceeding 100 meters. With structures of such height, wind turbines become more susceptible to lightning strikes. Since many of the favorable locations for wind energy also have thunderstorms, it is advisable to design a lightning protection system for wind turbines and wind turbine farms.

In contrast to the wind turbines, large photovoltaic power plants ranging from 100 kW to multimegawatts are still a few meters high. Tall photovoltaic plants are those secured on pedestals, and again, their height ranges from approximately five meters to twenty meters. Perhaps, the photovoltaic plants which are a bit more exposed to lightning strikes and lightning effects, are those installed on building roofs. The lightning threat to photovoltaic plants is significantly smaller when compared with the threat to wind turbines.

The amount of damage to a turbine component depends on its location, shape, size, and physical properties. For example, a straight section of aluminum blade would not be damaged by a normal lightning strike. Direct strikes can cause damage to the tower, blades, nacelle and connecting power and communications lines. Components that are vulnerable include blades, bearings, the generator, electronic controls, sensors and computers. Electronic components are particularly susceptible to damage. Electronics can suffer damages not only due to direct strikes to the turbine but also from nearby strikes, due to transients. At an unprotected site, it is possible to sustain damage which can have a significant economic impact in terms of repairs and in shutdown time [1]*.

Protection of the turbine components as well as of photovoltaic arrays is accomplished in a variety of ways. The method of protection, is in general, based on providing alternate paths for lightning currents. Thus, the design considerations for lightning protection are [2]:

1) Lightning characteristics.
2) Grounding, Shielding, and Bonding.
3) Surge, protection of Electronics.
4) Power system protection.
5) Blade and mechanical component protection (for wind turbines only).

It is known, and wind turbine designers should be familiar with the hazards posed by lightning, that lightning has killed people and animals, shattered trees, caused fires, damaged airplanes, set off munitions that have killed thousands of people, and caused millions of dollars of damage to appliances and electronics. [3] Hence lightning protection is a **matter of design** and must be incorporated into the overall design process.

The objectives of this study can be summarized into:

1. Review current knowledge on lightning and lightning protection methods on wind turbine and photovoltaic power plants.
2. Review published data on lightning stroke damages to wind turbine and photovoltaic power plants.
3. Critical assessment and recommendations.
4. Discuss findings with local experts.

* Numbers in brackets correspond to references listed at the end of this report.

2.0 LIGHTNING PHYSICS

2.1 Characteristics

Lightning is a naturally occurring phenomenon which can not be controlled or eliminated. A lightning stroke can develop localized temperatures of 30,000°K, currents ranging from several thousand amperes up to 400,000 amperes, potentials in the range of hundreds of millions of volts with event times in the order of microseconds (μs). Descriptions and discussions of the physics and mechanisms of lightning are readily available in literature. On the basis of the data available from numerous publications and especially as discussed by H. Bankaitis [4], the following parameters provide a sufficient description of the hazard, the naturally occurring lightning environment presents.

(1) **Peak Current** (kA) describes the current amplitude in lightning strokes, which can range from 3 to 400 kA, with most strokes exhibiting peak currents between 5 to 40 kA with 30 kA being a typical peak current. Current amplitudes exceeding 80 kA can be regarded as rare. This is one of the most important characteristics with respect to the damage that may be caused by a lightning stroke. The peak current is related to the explosive effect of lightning, the maximum voltage that can develop across ground resistance, the risk of side flashes, the possibility of sparking interfaces and so on. The first return stroke is generally of the highest amplitude.

(2) **Rate of Rise** (kA/μs) describes the rate of rise of lightning current, which can range from 5.5 to 100kA/μs, with the most probable range being 5.5 to 30 kA/μs. This characteristic is important in determining the amount of voltage that can be induced into electrical equipment. It is also used to determine the number of lightning conductors needed and their placement.

(3) **The action integral** $\int I^2 dt$ (A^2 s) expresses the proportional temperature rise in a metallic conductor when unidirectional current of constant amplitude flows through the conductor for a time.

(4) **The charge** (C) is most probably in the range of 3 to 20 C.

J.G. Keller, considers the following additional parameters as characterizing the lightning strike [5]:

(5) **Following Current Flow Durations** vary from about 10 to 10^3 microseconds.

(6) **Current Rise Times**, vary from less than 1 μs to more than 10 μs with 4 μs typical.

(7) **Field Recovery** or recharge time requires about 10 seconds before another stroke is possible.

(8) **Average Field Strength**: under a storm is between 10 and 30 kV/m. It rises to between 300 and 500 kV/m just before a strike. Field strength is potential voltage per unit length between the cloud and ground during a storm.

(9) **Cloud-to-Earth Potential** is estimated to exceed 100×10^6 V within an active storm area.

From the above data it can easily be seen that a lightning strike has the potential to cause severe damage at wind turbine and photovoltaics sites. Lethal currents can travel great distances down wire fences or instrumentation wires. A simulated lightning strike current profile used for testing effects of lightning strikes on equipment is illustrated in Figure 1.

The extremely high current rise frontal during a lightning stroke induces high voltage on lines not carrying the actual current. Thus, even if the stroke follows a good ground conductor, adjacent control or instrumentation lines may have induced voltages reaching thousands of volts. The potential induced will be a function of the circuit impedance, the distance from the conducting wire, and the rate of current rise. Current drive circuits and voltage limited circuits have a much better chance of surviving this type of phenomenon.

Typical lightning bolts dissipate 10^8 to 10^9 Joules in a fraction of a second. This is sufficient energy to raise the temperature of a ton of copper from room temperature to 1083°C, plus the latent heat of fusion energy to melt it into a liquid. In sharp contrast, the energy required to destroy vital electronic components is measured in millijoules [6].

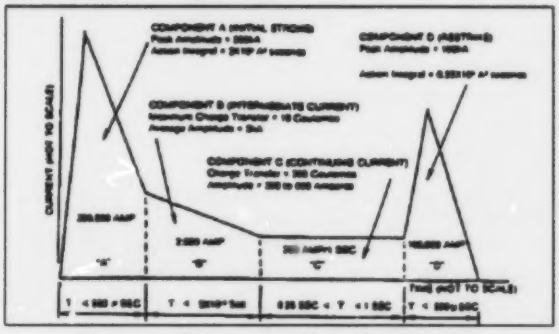

Figure 1. Current Waveform Components

Lightning currents vary from a few thousand amperes to hundreds of thousands of amperes. Lightning protection designs often use metal structural members of a tower or

conducting cables of sufficient size to carry the current to the ground. Nonetheless, even electrically adequate down conductors can experience enormous magnetic forces. For example, if a 54,000 ampere bolt splits its current between two parallel structural members located 10 cm apart, each would experience more than a ton of mechanical force per meter of length.

Potentials of millions of volts may be present over distances of just a few meters. Such voltages may cause flashovers, ionized arcs through air or insulation, as breakdown potentials are exceeded.

2.2 Probability of Strike

Given a predetermined site location, it is possible to obtain probability estimates of the frequency of strikes to a particular wind turbine and photovoltaics. These calculations are based upon isokeraunic maps showing the average number of thunderstorm days per year. For tall structures, the "average" number of strikes per year, S is related to the "average" number of thunderstorm days, T, and the height, h, in meters of the structure by the empirical equation, [6].

$S = 4 \times 10^{-6} h^2 T$ (strikes per year)

Thus, a 50 meter wind turbine located in a 50 thunderstorm day region would "average" one strike every two years. However, substantial deviations from the calculated values may occur because of variations in local weather and surface topography.

A model of lightning current usable by engineers responsible for lightning protection design is shown in Figure 2.

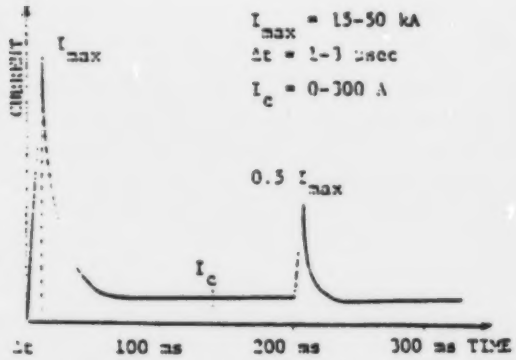

Figure 2. Model of Lightning Current

The number of return strokes is generally chosen between 3 and 5 for calculation purposes. Return stroke amplitudes are typically assumed to be 50% of the previous return stroke. Worst case maximum currents of 100,000 amperes are often employed. For the 50 meter turbine of the previous example such a large current strike could be expected once per two decades.

The rate of change of current is needed to calculate the voltage drop along any conductor carrying the lightning current. Typical rates of change may be calculated from Figure 2. The worst case rate of change is often chosen to be 100,000 amperes per microsecond.

Although a typical lightning stroke will release more than 10^8 joules of energy, more than 50% of the energy is associated with the physical phenomena of the discharge channel. The typical value of charge transfer during a lightning flash is not well established because the continuous current portion (see Ic in Fig.2) may not be present or may be of short duration. For example, a continuous current of 100 amperes for a duration of 0.5 seconds would transfer 50 Coulombs, a much higher value than normally reported in literature.

2.3 Thunderstorm Days

A thunderstorm day is generally defined as an observational day during which thunder is heard at the meteorological station; precipitation need not occur. Figure 3 [7].

The probability of a strike to an object is related to the ground flash density at the site. Ground flash density is the average number of lightning strikes to earth for a given area and time period. This quantity is usually expressed in number of flashes per square kilometres per year. Unfortunately, few data of ground flash occurrences are available. The ground flash density can be estimated using the isokeraunic level for a region. The estimated ground flash density can be translated into "probability of a strike" to a structure as a function of structure height. Caution on using these approximations should be observed since the isokeraunic level does not distinguish between the cloud-to-cloud and the cloud-to-ground flashes, nor does it account for storm duration, the number of storms in one day, or the local terrain, all of which can affect the probability of a strike. Methods of estimating the ground flash density from the isokeraunic level vary widely depending on the researcher and the data obtained. For example, in an isokeraunic area of 10 the ground flash density has been estimated to be somewhere between 0.5 and 2.0 flashes per square kilometre per year. To further complicate matters, the relationship between ground flash density and the probability of a strike as a function of structure height is also very much unknown. While most researchers agree that it is dependent on the area that the structure shields, the actual calculation is at best an approximation since it depends on several variables ranging from structure grounding to local topography, soil and ground water conditions.

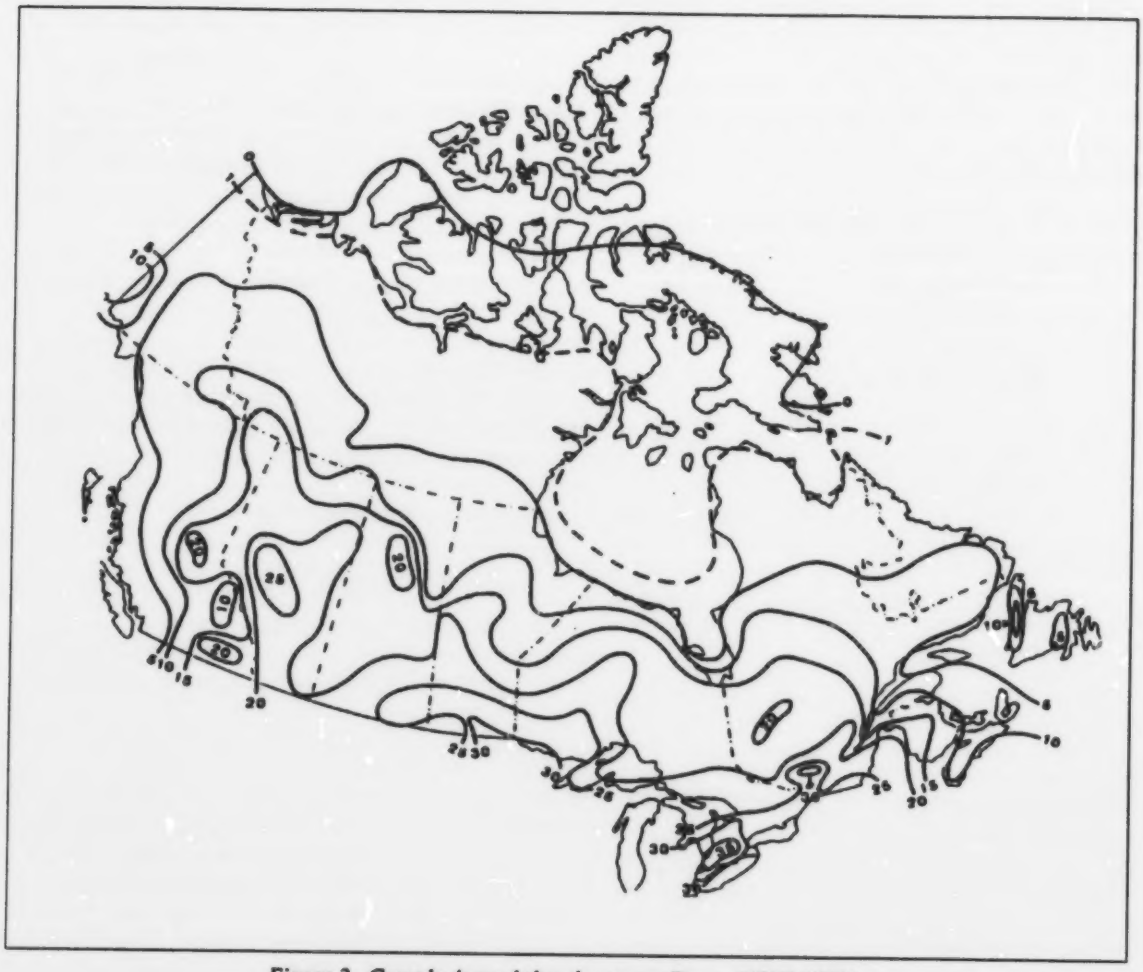

Figure 3. Canada Annual thunderstorms Days. (1957-1972)

3.0 LIGHTNING PROTECTION METHODS

3.1 Lightning Rod

Scientists and engineers realized over two hundred years ago that since they could not eliminate the naturally occurring lightning strokes, then, perhaps, they could introduce some kind of lightning protection for buildings and other facilities and for the public.

Hence, the introduction of the lightning rod, usually installed at the highest point of a structure in order to protect a specified facility or ground area from lightning strokes, by attracting all strokes to the rod. The lightning rod, was always connected via a down-conductor to a good earthing point or rod. As is well known, the lightning rod was first introduced by Benjamin Franklin in 1753. During the more than 200 years since its introduction, many theories and hundreds of papers were presented to define the zone protected by the lightning rod. This large number of theories was promoted, in a way, by the fact that major characteristics of the lightning were not well known. But each of these theories, coupled with the experience obtained from observations and experimental evidence, contributed to our current state of knowledge. The confirmation and extent of the zone protected by the lightning rod was determined primarily from experience. But this evidence differed from place to place as evidenced by the variability in national electrical codes relative to lightning protectors [8].

Recently, improved knowledge of the atmospheric electrical discharge and its governing physics, paved the way for new theories. These new theories, address some questions such as the protected space around a lightning rod and provide a better assessment of the protected areas by the lightning rod.

3.1.1 Lightning Rod Protective Zone

Over the many years of installation and observing the operation of lightning rods a formula was empirically developed and widely accepted, that the protective zone afforded by a lightning rod is that of a cone, with a 45° angle of protection. This is clearly reflected in the electrical codes of many countries, while some countries opted for a 60° angle of protection. Another dictum widely accepted by the lightning protection community for many years, is the principle of the shortest distance", i.e. the lightning stroke seeks out the ground object closest to the charged cloud. [8]

Golde, in his laboratory research [9,10] established that the striking distance to a lightning rod cannot be described by just one value. He further introduced a new concept of the attractive effect and protected zone of a vertical lightning rod, that is, the protective zone of a freestanding vertical lightning rod be described by a rolling ball about the rod. This is called the rolling ball theory, see Figure 4.

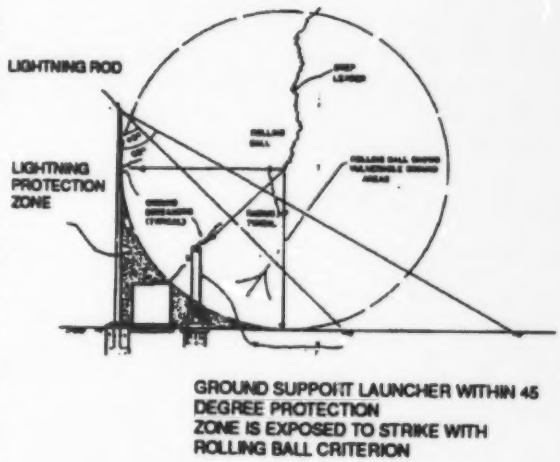
LIGHTNING ROD
LIGHTNING PROTECTION ZONE
GROUND SUPPORT LAUNCHER WITHIN 45 DEGREE PROTECTION ZONE IS EXPOSED TO STRIKE WITH ROLLING BALL CRITERION

Figure 4. Rolling ball theory of stroke.

As shown in Figure 5, the streamers will initiate off a lightning rod when the threshold gradient is exceeded and the threshold gradient is determined by the incident electric field resulting from an approaching step leader as well as by the height and radius of the tip of the object. This can be conveniently examined mathematically by use of a prolate spheroidal geometry to represent the lightning rods which permits a close approximation of the tip gradients. Thus the tip radius is critical in determining protection zones and height cannot be considered alone. The rolling ball theory of protection appears consistent with strikes to objects below a 45 degree cone of protection and is a more realistic as well as a more conservative approach.

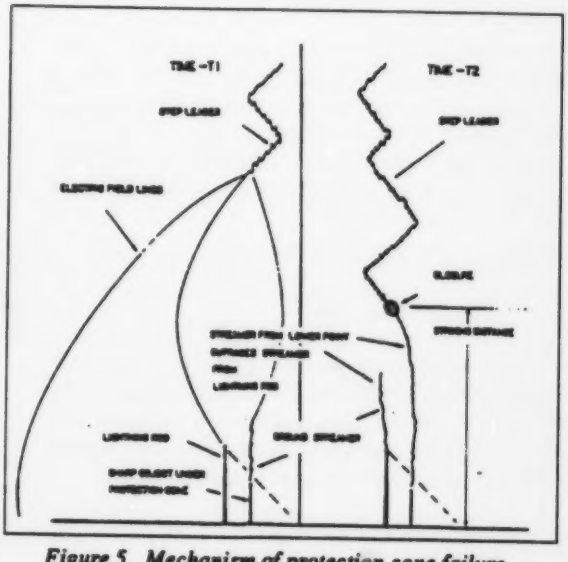

Figure 5. Mechanism of protection cone failure

3.2 Overhead Ground Wire

The above arguments support the use of catenary wire protection systems, such as used on space shuttle and in effect on power transmission lines (the overhead ground wire) and at open-air power sub-stations. This approach, though not practical for wind turbines due to the associated height and the need for a separate structure to support the wire (which involves substantial costs) could be used in other applications where the height is less prohibitive, e.g. for power lines, photovoltaic systems, etc.

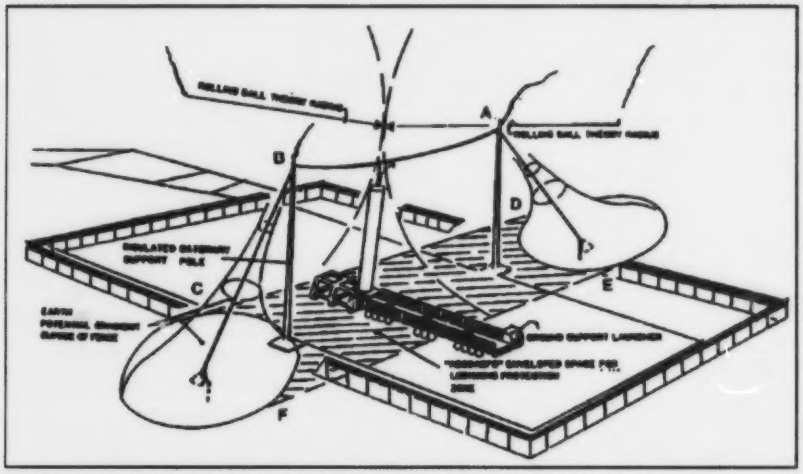

Figure 6. Lightning protection zone in the catenary wire system to protect a tall launcher.

This approach is illustrated in Figure 6 for a rocket launch area. With a wire overhead, much surer protection is provided than with a rod because of the relatively small area covered by the rod.

3.3 Hardening against lightning

Hardening against lightning or lightning effects is the methodology used to equip your hardware (wind turbine rotor, photovoltaic systems frame etc.) and to select such material components (such as resistors, capacitors, integrated circuits etc.) that can withstand repeated direct strikes or withstand repeated lightning strike effects (electromagnetic radiation, induced voltages etc.) without any damage.

3.4 Pre-emptive strikes

This is another method of lightning protection, primarily used to protect areas of prime importance, by firing from the ground wire-guided mini rockets which travel through the heavily charged clouds and initiate lightning strikes, normally cloud-to-cloud.

This method, is clearly not meant for wind turbines or photovoltaic installations, however further research is under way.

3.5 The Dissipation Array System (DAS)

The Dissipation Array System (DAS) was designed by Ray B. Carpenter Jr. to prevent lightning strikes [11]. The author states that this new form of lightning protection was first introduced in 1971. Since then, over 500 DA systems have been installed in many parts of the world.

The Dissipation Array System (DAS) consists of thousands of sharpened points enhanced by the electrostatic field always present in any weather condition. Figure 7 presents a conceptual example. When there are fair weather conditions, DAS, as well as the ground, is charged negatively with respect to the ionosphere and produces very small (tens nanoamperes) negative charges flow into surrounding DAS air, particularly from tall structures.

The following is the abstract of the review covering the above system:

"During the last 12 years, hundreds of DAS have been installed within the USA and many other parts of the

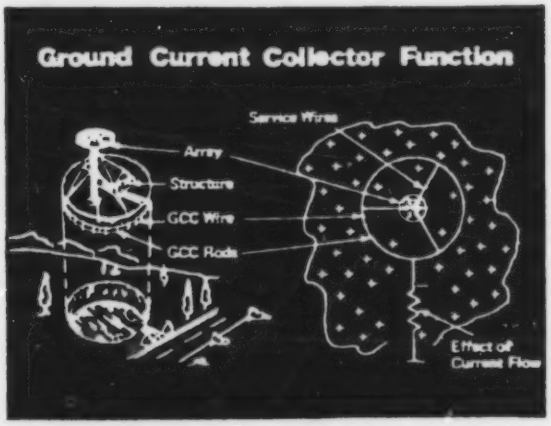

Figure 7. Dissipation Array System Concept

world. The statistical study of their performance gave the following results: 90% of the installed systems did not have a single lightning strike; 9% showed about 90% reduction in the number of strikes; less than 1% reported little or no changes. The study continued to

analyze the successes and failures, comparing site and array characteristics with the histories of performance, i.e. before and after data. The results of the study were conclusive: (1) They vindicate the premise that lightning strikes to a given facility can be prevented, regardless of the apparent difficulty; (2) they demonstrated the need for careful attention to the site and facility character, as weaknesses that require further clarification to permit achievement of almost 200 percent successful system design".

3.6 Radioactive Head. - HELITA

A radioactive head, manufactured by HELITA of France, is another form of lightning protection, used primarily overseas. The manufacturer claims 150 meters protective radius for each installed radioactive head.

However, there is a lot of skepticism about the effectiveness of this protection system, since there is no scientific or even experimental data to back-up the manufacturer's claims.

4.0 LIGHTNING PROTECTION OF WIND TURBINES AND PHOTOVOLTAICS

4.1 Rationale for Lightning Accommodation System

Even if the probability of the wind driven turbine generator structure being hit by lightning is low, the involvement of complex research instrumentation, mechanical hardware, and personnel at the sites may warrant the establishment and use of economical and proper lightning accommodation systems. The establishment of criteria to be consistently met by a suitable lightning accommodation system is influenced by factors encompassing economics, manufacturing, materials and interference with the environment. The roles of these various factors were evaluated, and a series of ground rules were established by Lewis Research Center; the lightning system should be [4]:

(1) Capable of dissipating the energy imparted by a lightning strike without deleterious effects to personnel, structure or instrumentation.
(2) Economically feasible to install and maintain.
(3) Compatible with the processes by which wind driven turbine rotor blades are manufactured.
(4) Capable of withstanding repeated lightning strikes.
(5) Easily repaired in the field.
(6) Non-interfering with television reception, navigational or communications equipment functions.

The effectiveness of any given lightning accommodation system is predicated on the conductivity or lack thereof (resistance) of the ground on which the wind driven turbine generator structure is built. Grounding grids commensurate with the ground conductivity must be considered early in design phase of the site, the structures at the site and the lightning accommodation system for these structures and their integral components.

A direct strike to wind turbines can damage, blades, structure, generator, and any other mechanical component. Damage to electronics control and decision making computers can occur from indirect strikes, i.e. nearby strikes, which could induce substantial voltages and currents on the electronics, and consequently damage them.

The lightning protection to a wind turbine, can be subdivided to the protection assigned to each major component of the wind turbine. That is:

(1) Electrical power system protection.
(2) Blades and mechanical components protection.
(3) Electronics protection.
(4) Grounding, Shielding and Bonding protection.

4.2 Protection to Horizontal Wind Turbine (HAWT)

4.2.1 Electrical Power System Prosection

Placing a generator on top of a tower increases the chances of lightning damage to the generator and its components. Generally equipment normally used by utilities is located below ground level. Its location within the plant shelter gives it protection not available to wind turbine generating equipment.

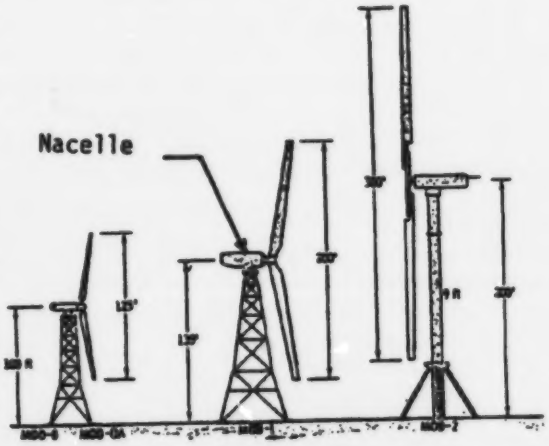

Figure 8. Electrical Power Protection

The illustrations in Figure 8 show wind turbine blades in the vertical position. In this maximum height position a lightning current path from the blade tip to the generator exists. However, in order to reach the rotor of the generator, the current would have to pass through bearings, the gearbox and the low speed and high speed shafts. The electrical power system for a wind turbine consists of a generator and the power lines connecting the turbine to a power grid. In most cases a synchronous machine or an induction machine is used for the generator.

A strike on the nacelle, already shown in Figure 8 or tower could induce voltages and currents in the generator winding. Surges from lightning or power line switching could also damage the generator. Figure 9 shows diagrammatically the generator lightning hazards [1].

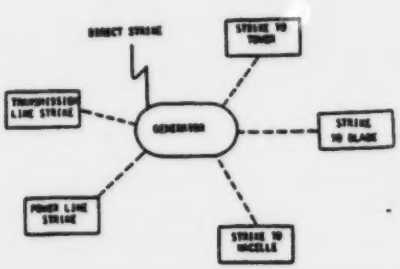

Figure 9. Generator Lightning Hazards

Direct strike damage to the electrical power system may result from lightning strikes to 1) the blade, 2) the structure around the generator, 3) the tower, 4) the power lines, or 5) the power grid. Windfarms may have their own distribution system within an array introducing another source similar to the power grid. The basic technique for protection will be the same in either case, with the only difference in this instance being that the protection would be provided by the windfarm operator, and not the utility.

Providing protection to a synchronous generator or an induction generator is basically the same. If the electronically controlled excitation system for a synchronous generator is protected using lateral and longitudinal protection, the remaining portion of the protection technique is the same, see Figure 10. A fundamental protection system for generators is shown in Figure 11. The purpose of the arresters is to limit peak voltage. The inductor and capacitor arrangement limits the time it takes a surge voltage to reach its peak. This arrangement or a variation of it is considered as the basic surge protection technique for rotating electrical machinery.

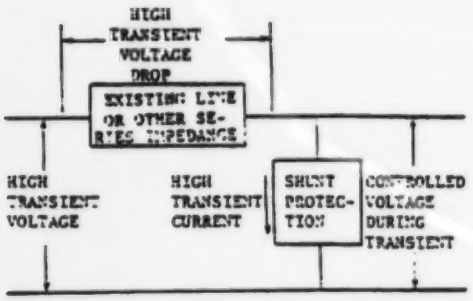

Figure 10. Synchronous Generator Protection

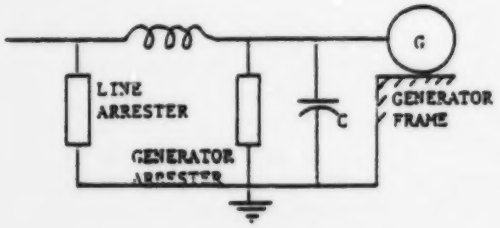

Figure 11. Fundamental Protection System for Generators

It is considered to be a good lightning protection procedure to have all the electrical and mechanical components of the wind turbine inside an electrically continuous metal enclosure. If openings in the enclosure are kept to a minimum and shielded when possible, the percentage of lightning energy entering this equipment container will be small. Electrical by-pass brushes on the low-speed shaft connected to the blade will minimize the strike energy entering from a direct strike to the blade.

Procedures have been established for protecting rotating equipment from electrical surges. For example the IEEE text [12] does an excellent job of discussing surge protection design principles for electrical power system. The details in that text are too lengthy to be contained in this review.

4.2.2 Blades and Mechanical Components Protection

Lightning strikes that directly hit the wind turbine will probably attach to the blade. The damage occurring to the blade could cause shutdown and expensive maintenance. The blade and hub usually represent one-fourth of the cost of a modern machine and may be the most expensive to replace. The blade is not only the link between wind energy and the mechanical energy going to the gearbox, but could be a lightning link to all the equipment associated with the wind turbine [13].

Some experience exists in dealing with strikes to aircraft surfaces. Even though most aircraft lightning strikes are from cloud-to-cloud similar protection techniques are applicable to ground based wind turbine blades.

Reference [14] published in October of 1977 is the source of much of the information that follows. Lightning strikes to metal aircraft wings illustrates what might be expected if a metal wind turbine blade sustains a direct hit. Composite materials that have been proposed in blade construction normally are poor electrical conductors and could be damaged if a lightning protection system is not provided. Fiberglass radomes with no lightning protection have been rendered useless and hazardous to flight when struck by lightning.

Steel and aluminum were the major metals used in blade construction at the early stages of wind turbines, and are still commonly used today for VAWTs. Fiberglass, wood epoxy and kevlar are now used for HAWTs. These are not good conductors, thereby requiring some additional measures in providing lightning protection. Even though the metallic structure used in blades serves as a good conducting path, damage can still occur to metal blades. The damage that can be expected to metallic blades includes melting at lightning attachment points, magnetic stress and pitting from arcing at discontinuities.

A discussion of melting at attachment points indicates that it should be of little concern to manufacturers of metallic blades. Temperature rise of metallic blades carrying lightning currents is temporary and probably will not effect structural integrity. Magnetic forces

resulting from large lightning currents and certain blade geometries could cause damage such as permanent bending and/or fatiguing of the blade structure. Forces on bonding straps which are used to connect metal to metal can damage them and also cause damage to nearby structures. These forces result from the interaction of current carrying conductors and magnetic fields. The magnitude of these forces depends on the system geometry, current magnitudes and directions, permeability, and separation distance. For example, two parallel conductors, each carrying 50,000 amperes and placed 2 centimeters apart in air, will experience a force of 25,000 N/m (1,713 lb/ft). Bonding straps should have sufficient cross sectioned area to carry lightning currents; they should be short; bends should be smooth and not less than 45 degrees and parallel straps should be sufficiently separated [14].

The following principle for providing protection to non metallic structures can be used for accommodating strikes to blades. By providing a good conducting path on the surface of the non-conducting blade, lightning currents will not flow inside the structure. There are several ways of implementing this principle such as attaching conductive tape, conductive paint, aluminized glass cloth or metal glass cloth, diverter strips and screen mesh. Compatibility with manufacturing processes and other factors should be considered in the design of lightning protection of blades. Coordination with vendors of these materials is a recommended step before reaching a decision on the method of protection.

In order to establish the validity of a lightning accommodation system a test program would normally be necessary. Guidelines for such tests are contained in the SAE Committee AE4L Report [15]. The summary of test results given by Bankaitis after a series of blade tests should be of value to blade designers [16].

4.2.3 Electronics Protection

The information that follows, was primarily obtained from References [6], [17], [18] and [19]. A procedure for determining how much protection and at what level is needed between the external lightning environment and the circuits inside equipment is developed on the basis of **nested shields** or electromagnetic barriers. Part of this protection is usually placed at the system level (at the aircraft skin, or at the nacelle enclosure) and part may be placed at the equipment level, i.e. box level.

In general, the electromagnetic barrier must be impervious to all electromagnetic waves -- those that propagate through space as well as those that propagate along wires or other conductors. Although a closed metal shield is very effective in excluding electromagnetic waves from the volume enclosed by the shield, almost all practical applications of shields require that power and signal wires pass through the shield and that openings be made for ventilation and visibility. As illustrated in Figure 12, penetrating conductors can reduce the shielding effectiveness of the shield down to zero, since the wire current and the magnetic field about the wire are the same inside the field as they are outside the shield at frequencies where the wire-to-shield capacitance is negligible. Where the apertures dimensions are large (in terms of wavelength), incident space waves can propagate through the apertures virtually unattenuated. Hence, signal and power wires negate the shield at low frequencies, and vents and windows negate the shield at high frequencies.

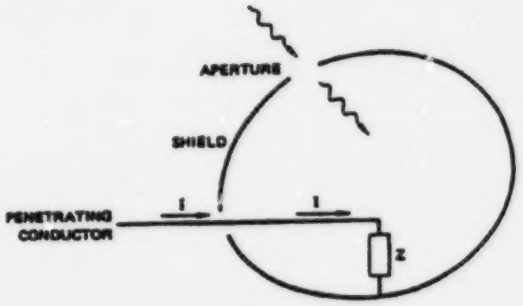

Figure 12. Penetrating conductors into shields

Because a practical shield with penetrating conductors and apertures is usually ineffective in excluding electromagnetic waves, the term "electromagnetic barrier" is used to describe a surface that is impervious to both space and guided waves at all frequencies of interest. The electromagnetic barrier usually contains a shield to exclude space waves, but it also contains devices, such as filters on penetrating wires, to exclude waves guided along these conductors, and various aperture treatments, such as waveguide-beyond-cutoff structures, to exclude waves propagating through these openings.

All semiconductor devices are susceptible to electrostatic discharge failure, (whether from lightning or some other source such as static charge), independent of the semiconductor technology utilized in the manufacturing of the device. Differences in vulnerability to static discharge currents between different devices and device technology do exist. Typical breakdown voltages for semiconductor devices is shown in Table 1 [18]. Metal oxide semiconductors (MOS) structures are particularly prone to static discharge damage due to dielectric breakdown at gate junctions where the electric field may be quite high. Integrated circuits can be protected by the inclusion of static protection circuitry. It is, however, quite easy to have lightning induced static discharge with potentials exceeding the limits of a protective network.

Table 1.
Typical Breakdown Voltages for Semiconductors [18].

Device Type	Electrostatic Discharge Susceptibility (Volts)
MOSFET	10-200
JFET	140-10,000
CMOS	250-2,000
SCHOTTKY DIODES, TTL	300-2,500
BI-POLAR TRANSISTORS	300-7,000

Thunderstorm build-up also results in a build-up of the static field between the earth and the storm cell. Electric field strengths vary from a few hundred volts per meter to tens of thousands volts per meter. Many wind turbines under test today have a portion of the electronics in the nacelle which may be located between 50 and 200 feet above the earth. The potential difference between an object located at that height and the ground, during a static field build up, can be very large. Although shielding is provided by the nacelle shroud and other structures, it is possible for discrete and integrated components to build up a static charge themselves. This electrostatic charge may reach a critical potential at which dielectric breakdown may occur.

As a general rule, some conductor devices (discrete and integrated) are most susceptible to transient damage. Resistors, capacitors and inductors can withstand powers approximately 10,000 times their power rating for microsecond pulses.

Protection Procedures

Transient response and failure studies indicate that for maximum protection of electronic circuitry from direct and induced lightning discharge a series of general steps must be taken.

1. Analysis of circuit transient response utilizing an appropriate lightning current waveform model.
2. Response of circuit elements to induced and direct current injection.
3. Shielding of input/output leads and circuitry.
4. Proper grounding of structure and electronics.
5. Selection of components during design phase of circuit which will provide the best failure statistics.
6. Transient protection provided at the circuit with inclusion of protective devices and circuit design techniques.

One of the greatest problems associated with the protection of wind turbine electronics is the isolation of electric components and systems from high voltage and current transients entering through data transmission lines. There has been some misconception in the past that lightning must strike at, or very near a data line in order for damage to occur to the electronics. This condition may cause the greatest amount of damage but is not the only, or even the most frequent mechanism by which damage or fatigue can occur due to lightning discharges. It is quite possible for the lightning strike to be some distance from the electronics and still induce a transient through the data line or other input aperture to the electronic circuitry.

Electronics must play a key role in the wind turbine system to provide critical safety and control functions. To provide the electronic decision circuitry with system operation information, sensors are utilized to detect such parameters as wind direction and intensity, blade icing, generator and power line voltage and phasing, etc. This data is necessary to coordinate wind turbine power generation with power system needs and operation as well as to shut down the wind turbine operation when unsafe conditions occur. This latter function of the electronics requires additional attention to prevent spurious action caused by occasional misinformation (and thus mis-decisions) by the electronics when subjected to lightning generated transients. Not only must electronic circuitry be protected from direct destruction, but also from behavioral aberrations. The numerous effects of lightning on wind turbine electronics is illustrated in Figure 13.

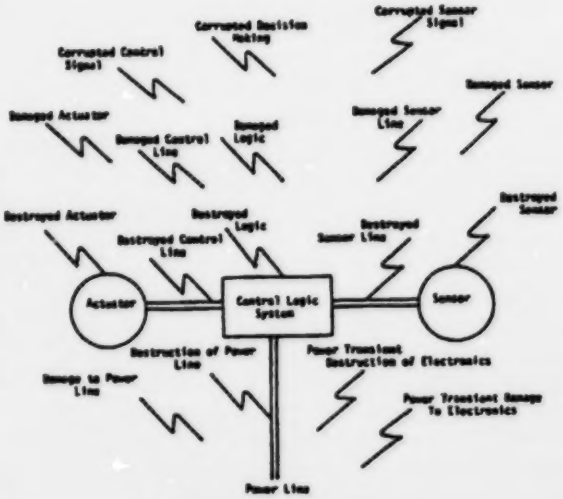

Figure 13. Damage to electronics

Both power and communication lines must be protected from primary and induced transients with rise times of a few microseconds, and durations of many milliseconds. To accomplish this task, several layers of protection are usually required to neutralize the full effects of the transients strike threat to the electronics. Heavy arresters are needed to drain off the large amount of

energy in primary and induced transients. Very fast acting solid state circuit protectors must be located close to critical electronics. A lightning arrestor may also be used to protect the power and signal lines from very large voltages and currents. Redundant sensors located at separate positions on the turbine may be needed for selected critical measurements, if operation is to be continued after the destruction of one sensor by a strike. Special software precautions must be taken within any system computer to guard against temporary erroneous data received or processed during a lightning initiated transient, as well as detection of destroyed or damaged sensors or actuators. Direct strike lightning current must be routed well away from both the electronic circuitry and the input/output lines. This will minimize resistivity coupled, and also induced voltage and current transients into the circuitry. An example of the "layer of protection" philosophy is illustrated in Figure 14.

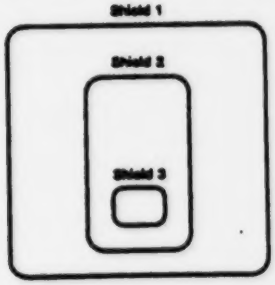

Figure 14. Nested barriers

4.2.4 Grounding, Shielding and Bonding Protection

4.2.4.1 Grounding Protection

One objective of lightning protection is to divert the lightning current through low-impedance, non-critical paths to ground. The lightning-protection designer should minimize high current paths near enclosures that contain sensitive components.

For most horizontal-axis machines, the supporting steel tower structure provides the lowest impedance path to ground. With most of the current flowing along the outer extremities of the tower, the magnetic fields inside the structure are greatly reduced. For non-conducting towers, a minimum of at least three down-conductors equally-spaced about the periphery of the cross-section of the tower should be used [13].

Additional equally-spaced down-conductors will further reduce the magnetic coupling inside the tower if they share the lightning current. Sharing is accomplished by common connections. Particularly critical are the common connections near the top of the tower. Such connections should be made at natural equipotential surface. For tall structures these surfaces should be horizontal planes.

The nature of the wind forces on a wind turbine requires a tower base of considerable mechanical strength. Because concrete behaves electrically very much like earth, such a base is conducive to the design of an effective lightning path to earth. It is very important to incorporate the design of the electrical ground system into the initial design of the tower/base/pad/ foundations/piers/footing/rock anchors, etc. These structures extend into the earth, and they require reinforcing bars that can also serve the purpose of conducting lightning current to ground. There are a number of communication and power transmission line tower foundations in existence that were designed to serve the suggested dual function [13].

Normally, the tower load is transmitted through steel baseplate to a concrete foundation or appropriate footing. The baseplates are attached with anchor bolts which extend into the concrete and which can be connected electrically to parts of the reinforcing bar system. When the steel reinforcing bar system is utilized as a portion of the ground electrode, the electrical connections between the tower (or other-down conductors) and the ground electrode are most critical. The connection must be welds or mechanical electrical connections that are currently approved electrical bonds.

Inside the concrete, the reinforcing bar to which the tower/down conductors are solidly connected should be as long as practically possible, and it should be in contact with a large number of other bars. It is strongly recommended that additional approved bonds be made until the accumulated length of solidly connected bars extends at least twenty feet [24]. This recommendation applies to each of the ground electrode connections which normally number three or four. Many other reinforcing bars should be in physical laying across it or by physically tying bars together with tie wires. The desired net effect is to have the entire reinforcing bar network act as a single three-dimensional ground grid, see Fig.15, [13].

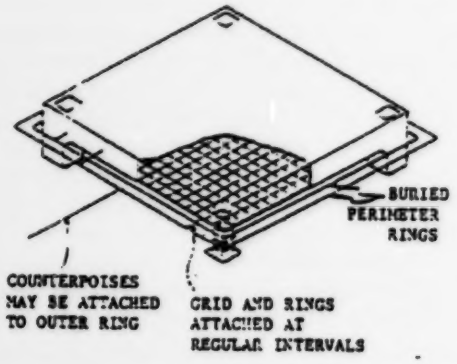

Figure 15. Ground System Consisting of Reinforcing Bars, Rings, and Counterpoises

In addition to the portion of the ground electrode formed by the rebars in the tower footing, it is standard practice to bury one or more conducting rings just outside the foundation in the soil. These rings are critical for personnel safety. Properly placed rings reduce sideflashing and dangerous "step" and "touch" potentials, see Figure 16. Counterpoises may be attached to the rings to further reduce ground resistance.

Although numbers for body resistance vary somewhat, 1000 ohms is assumed for computing currents from step and touch potentials. The length associated with the step potential is assumed to be one meter. Step potential danger, on the other hand, is of concern where the soil resistivity is high. In situations where the design does not yield safe conditions, it is recommended that the site be fenced and that personnel vacate the site during thunderstorms.

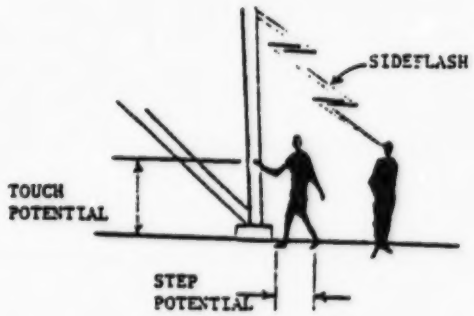

Figure 16. Step and Touch Potentials and Sideflash

When lightning strikes a wind turbine the entire structure acts as a transmission line. Voltage and current reflections are produced whenever a surge encounters discontinuities in the line. The point of connection of the tower to the ground network is generally the dominating discontinuity.

Grounding Techniques

Michael F. Stringfellow, [20] provided an in-depth analysis of the different practices used for grounding and bonding of power and lightning protection systems and sensitive electronic equipment.

The most frequently encountered grounding techniques, are briefly described below:

(a) Single Point Grounding.
This is frequently specified for sensitive electronic equipment as a method for eliminating the flow of noise currents in ground wires.

(b) Multiple-Point Grounding.
This is the most common found technique in practical installations in large facilities. If the multiple-ground points are interconnected by low impedance bonding, the technique works satisfactorily.

(c) Isolated Grounds.
Probably one of the most mis-used techniques for protection of computer and electronic equipment, with installations made in violation of safety codes and standards. Attempts to install isolated, "clean" or "floating" grounds not connected to the power source ground are dangerous and troublesome.

(d) Ground Reference Plane.
It is a low impedance ground installed within a building to minimize high frequency noise and surge voltages between equipment.

(e) Lightning - Protection System Grounds
Most lightning protection codes specify that a structure be equipped with a ground network to dissipate lightning currents into the grounds. The use of the power safety ground for this purpose is not allowed in most codes.

4.2.4.2 Shielding and Bonding

Indirect effects of lightning strikes [17], i.e. induced electric and magnetic fields, can induce currents with sufficient energy to disable the electronic components temporarily or permanently. Induced or indirect lightning effects can be reduced by proper shielding of the electronic circuits. Shielding enclosures can be constructed of any conducting material. The shielding performance of an enclosure decreases in the vicinity of any door, cable entrance, or other aperture. Therefore, it is necessary to maintain electrical continuity between such openings and the enclosure. To provide continuity at door openings, flexible brass fingerstock may be attached to the door. For smaller apertures, electromagnetic gaskets are normally used. Power supply and communication lines must penetrate the shield. These penetrations weaken the shielding performance, and require additional care to prevent undue exposure of the electronics to high transients fields. A metallic continuous solid-wall cylindrical outer shield should be used. This outer shield should not be used as a signal return path when used for electric and magnetic shielding. The cables inside of this shield are braid shielded and twisted so that equal voltages will be picked up by each cable. Grounding must be done in such a way that the induced interference current will be diverted to the exterior surface of the solid-wall shield. Grounding conductors should not be allowed to penetrate the outer solid-wall shield.

Grounding Topology

As noted above, grounding conductors may compromise the shield if they pass through as insulated conductors [21]. It was also noted that they are groundable. Hence, grounding conductors should be bonded to the shield instead of passing through the shield so that any current on the grounding conductor will be delivered to the shield, rather than allowed to propagate through the shield on the conductor. To emphasize the separation on the interior ground from the exterior ground, we often show them displaced from one another (Figure 17). At dc, all grounds in the shielded spaces are interconnected, but the shield isolates them at RF so that RF interference in one shielded volume cannot propagate to another volume along the ground lead.

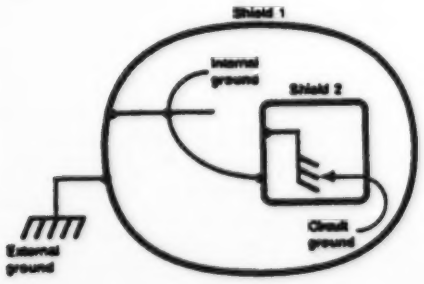

Figure 17. Grounding topology

For RF interference control, the fundamental grounding rule is that grounding network (or sub-system should be entirely within a shielded volume (Figure 18). Topologically, elements of the grounding network should not penetrate barrier surfaces. If this rule of grounding topology is followed, the ground systems cannot be the path for lightning and power switching currents to enter the electronic circuits [21].

Some commonly encountered grounding anomalies are illustrated [22] in Figures 19(a), (c), and (e). In Figure 19(a), the building shield is violated by routing a separate ground wire from the equipment cabinet to the earth electrode outside the building, thus contaminating the building environment. More serious violations are illustrated in Figures 19(c) and (e); in these examples, small-signal ground (signal common) is connected to a conductor exposed to the raw outside environment. Although such grounding arrangements have been used, they have been the source of much objectionable interference in digital systems -- at least upset and often damage. The correct shielding and grounding topology is illustrated in Figure 19(b), where it is seen that no grounding conductor penetrates a system shield. An alternative such as that shown in Figure 19(d) can be used to correct the severe violation of Figure 19(c), but this is usually a more expensive and less reliable approach. Another acceptable alternative is shown in Figure 19(f), in which the grounding conductor is continuous through both shields but the hole through which the conductor passes is filled by welding, brazing, or soldering the conductor to the shield material. As in the case of the filtered ground penetration, there is no particular advantage to the continuous conductor fused to the shields.

According to our shielding and grounding topology concepts, the treatment of the ends of cable shields is an act of shielding, rather than grounding. This can be seen in Figure 20, where the slender shield segment between the two "equipment housings" may represent the shield of an interconnecting cable. Since the cable shield is a part of the overall barrier for the enclosed circuits, the rule for cable shield termination is to close the overall shield. This generally implies peripherally bonding the cable shield to the terminal equipment housing with a clamp or connector [21].

4.3 Vertical Axis Wind Turbines (VAWTs)

4.3.1 Lightning Protection of VAWTs

J.G. Keller, of NRC in his paper [5], provides an in-depth analysis of the 500 kW VAWTs at Aquilo site. Most of the information that follows is from this reference.

4.3.1.1 Protection of the Machine

A sketch of a typical 500 kW VAWT (Aquilo) is shown in Figure 21. If lightning strikes the machine at its highest point, large currents will flow down to ground as illustrated by the arrows. The guy anchors for this machine are steel I-beams embedded in concrete. The 8 in. I-beam extends about 16 ft through the soil before entering the concrete foundation. The I-beam surface is bare galvanized metal, which provides an excellent path to ground. The power module at the base of the machine is well grounded with a heavy gauge copper coil buried below the foundation. This ground coil is connected to the steel structure of the module, as well as to the generator cases and switch gear enclosures, using heavy gauge copper wire. During a strike, lightning currents will tend to flow down the three pairs of guy wires to earth and also down the rotor column to the power module ground.

Critical areas of the machine that require protection are the bearings on the lower and upper ends of the rotor and the electrical apparatus. The DAF Indal 500 kW machine uses journal type bearings at both the upper and lower ends of the rotor. Very little is known about the effects and potential damage from lightning strikes on this type of bearing. The rotor when operating is

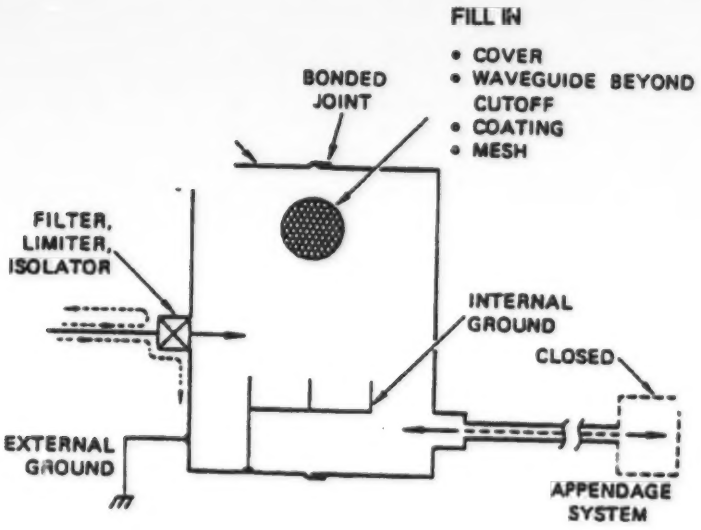

Figure 18. Elements of a typical closed electromagnetic barrier

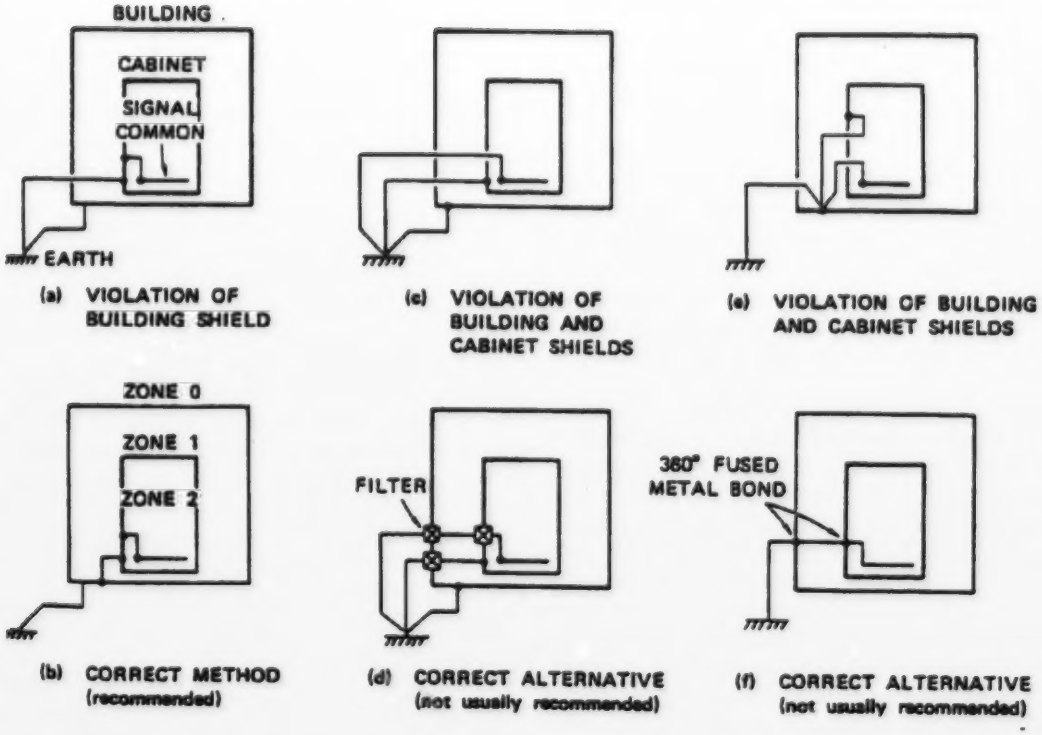

Figure 19. Typical grounding anomalies encountered in practice and some correct alternatives

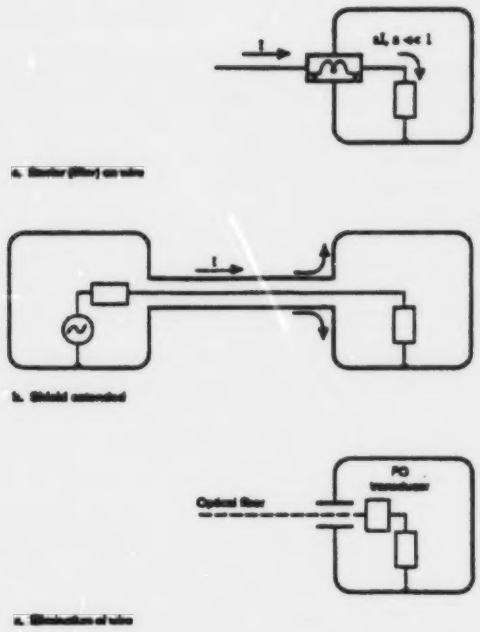

Figure 20. Completing a practical barrier

actually "floating" on an oil film which has a very high electrical resistance. This would tend to direct most of the current from the strike down the guy wires. Brushes have been proposed on the top and bottom section of the rotor to bypass any electrical discharge away from both the instrumentation wiring and the bearings. This is recommended on this type of machine to reduce the risk of lightning discharge damage. The DAF Indal 50 kW machines have such brushes installed.

Other types of damage that may occur when lightning strikes a turbine are from the large impulse currents that flow throughout the structure during a strike. Down conductors should be installed without sharp corners and should be secured at frequent intervals. Electromagnetic forces between conductors can be extremely high.

The blades on most VAWTs are virtually immune to damage even from a direct hit, since they are normally constructed of extruded aluminum, which is an excellent conductor. There have been no known reports of lightning damage to extruded aluminum blades. The amount of metal and overall size provides an excellent path for lightning currents. There would be a serious problem, however, if the blades were constructed of non-conducting material such as fiberglass. In this case it is advisable to imbed a wire mesh which is well grounded just below the blade surface or to cover the blade with a metallic material which can conduct any lightning current. There have been several reports of damage to non-metallic blades from lightning. The Swedish horizontal axis turbine at Maglarp has suffered damage to both the metallic covering on the blade leading edge and to strain gauges imbedded into the fiberglass.

Since Aquilo has extruded aluminum blades, no protection on the blades against lightning strikes was required. Power lines to the machine have been protected using standard techniques employed by the utility (buried cable where possible and the main transformers and lines protected with overhead ground wires and lightning arresters). In conclusion the main requirements to protect a machine such as Aquilo would be to:

1. Provide good solid grounds for the base and anchors.
2. Add brushes to by-pass current around the upper and lower rotor bearings.
3. Ground all switchgear, control cabinets, and generator housings by heavy gauge copper cable.
4. Use lightning arresters and overhead ground wires to protect power transformers and lines.

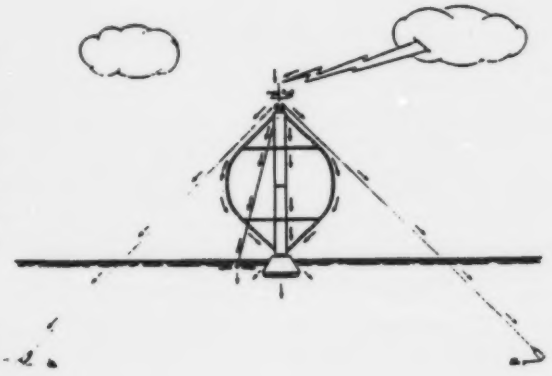

Figure 21. Paths of lightning current

4.3.1.2 Protection of the instrumentation and controls

The protection of instrumentation is probably the most difficult part of lightning protection because sensors tend to be very sensitive to high voltage/current surges and experimental turbines tend to have extensive sensor wiring on them. The following paragraphs illustrate how to minimize the damage, while realizing that some sensors may be lost if there is a direct strike.

A) Cone of Protection

Anemometers and other meteorological sensors which may be situated on top of the machine or on separate towers can be protected easily by lightning rods protruding above the sensor to absorb any direct strikes.

B) Circuitry and Sensor Protection

While in most cases there is a very limited selection in the type of sensor one can choose, it is beneficial to realize that some sensors can withstand voltage or current surges better than others. Anemometer heads which employ little, if any, electronics appear to have a better reliability with respect to lightning survival. Circuits which measure frequency can be designed to withstand large voltage surges by employing gas discharge varistor, voltage limiting protection circuits, or optical isolation techniques without causing any reduction in the accuracy of the readings.

4.3.1.3 Ground gradient protection

It is well known by farmers that cattle have a habit of gathering under isolated trees during thunderstorms. If the tree is struck by lightning, often several animals, if not all, are killed. This occurs even though few are directly hit by the stroke or any of the side flashes. The majority are electrocuted by the voltage gradient at the ground surface around the tree [6]. This voltage is caused by the lightning current. In high resistive soil an animal can be quite some distance from the tree and still receive a lethal shock. Figure 22 illustrates how a cow may be killed due to voltage gradient. When the turbine is struck the lightning current flows down the structure to the ground. From here the current spreads out radially through the ground to neutralize the charge in the earth. Since the ground resistance is fairly high and the lightning current is quite substantial, high voltage differentials are produced. The circles dotted around the imaginary turbine are equipotential lines. The illustration assumes the ground composition is uniform and of equal resistance; in reality these equipotential lines may be distorted due to local ground conditions.

For the protection of the Aquilo site against ground gradients a rather large ground mat was laid out. Copper wire was buried approximately 25-50 cm below the surface, interconnecting the three guy anchors and the module structure. Figure 23 shows the general layout of the Aquilo grounding. Ground rods were driven in at intervals along the cable to provide extra grounding. The anchors themselves are extremely good grounds. This system ensures that the area around the turbine is at a reasonable equipotential even during a severe lightning strike. Gradients beyond the protected area are likely to be low enough that damage or injury potential is minimal.

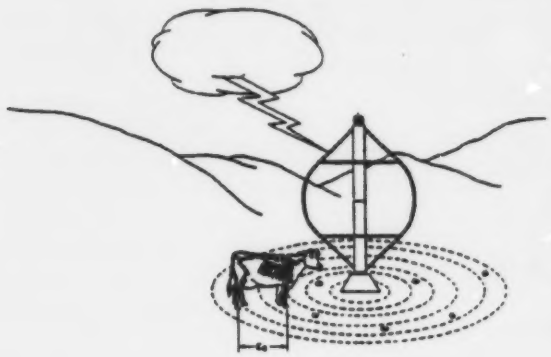

Figure 22. Ground potential kills a cow

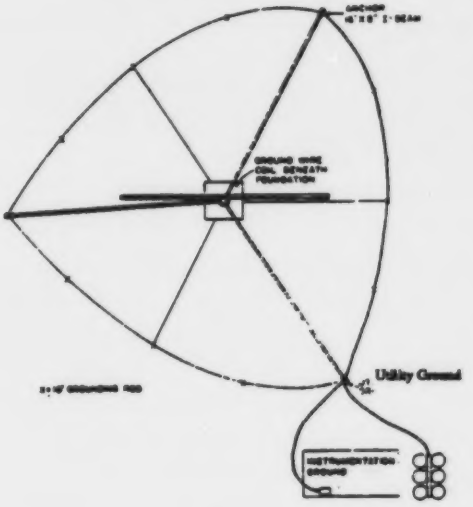

Figure 23. Grounding system for Aquilo site

4.4 Lightning Protection of Photovoltaic Power Systems

4.4.1 General

Electrical transients caused by lightning produce stresses in photovoltaic cells, cabling, power conditioning equipment and control circuits. This influences systems reliability and cost, so photovoltaic system engineers have sought designs which mitigate these adverse effects [23].

Systems and structures are protected from the effects of lightning by a combination of three techniques: (a) stroke interception, (b) shielding and (c) terminal protection.

Lightning protection for a photovoltaic power system is an integral part of the system design that ensures proper equipment operation and provides for the protection of equipment and personnel. The design of the protection scheme is influenced by several site-specific and system-specific considerations, such as the isokeraunic level (number of thunderstorm days per year), whether the system is standalone or connected to a utility, size, earth resistivity, and whether the array is ground or roof mounted [24].

A principal element of a lightning protection system is the grounding of the power system and the various pieces of equipment such as array structure, junction boxes, and conduits. One difficulty in assessing the cost of lightning protection systems is that the hardware such as grounds and transients suppression devices serve multiple functions such as minimizing electromagnetic interference, providing for protection from equipment failures, and also for protection against the effects of lightning.

4.4.2 Lightning Threat

Two studies [25, 26] concluded that the optical flash from lightning does not present a significant threat to cells of flat plate or concentrator systems.

The probability of lightning directly hitting a system conductor is small. For a 1-MW photovoltaic system (about 0.01 km^2) located at a site like Orlando, Florida, the probability of direct strike to the associated area is less than one occurrence in 12 years. However, for an area within a one kilometer radius at an Orlando site there will be 25 ground strokes per year. Therefore, the main threat from lightning to terrestrial photovoltaic power system appears to be from the coupling of lightning-generated fields to buried and above-ground system conductors.

4.4.3 Coupling considerations

Underground Cables

The dc power cables will be insulated wires, generally unshielded and may be routed underground. Control and instrumentation cables may be coaxially shielded and may also be routed underground. Transients induced in these cables will depend on soil resistivity, cable terminations, and cable parameters such as length, dielectric strength of insulating jackets, and the transfer impedance of the cable shield.

From a survey of measurements reported on buried cables and a review of several analyses of specific cable configurations, the following generalizations may be made: (a) voltage surges will generally be less than a few kV peak, and (b) current surges on cable shield and on insulated dc power cables will be less than 2 kV peak. These values represent reasonable worst cases to be considered in the design of protection schemes for equipment connected to underground cables [26].

Above-Ground Cables

In photovoltaic systems the dc wiring is "out in the open" in contrast to the conventional dc system which is within a building and adequately shielded from lightning induced transients. The above-ground power and instrumentation cables form geometric loops, i.e. ground, array, dc cable, inverter, ground. This loop coupling can stress the system elements in several ways.

4.4.4 Damage Thresholds

Solar Cells

Hamm [25] analyzed the failure modes of silicon solar cells exposed to lightning-induced electrical transients. Two predominant failure modes were determined to be (a) the melting of the metal grid on the illuminated face of the cell and (b) burnout of the semi-conductor junction (defined to occur at the onset of thermal instability). The same study also concluded the following about silicon cell susceptibility to failure from lightning: (a) metal failure current depends on the size of the main bus, (b) junction failure current depends strongly on the sheet resistance of the diffused layer, and (c) cells designed for concentrator applications generally have higher thresholds than one-sun cells.

Solar Cell Network Vulnerability.

Given the vulnerability of individual cells, the failure levels for networks of cells can be estimated. For a particular system design, the cells will be wired in a combination of series and parallel strings to produce the desired dc voltage and currents.

System components failure other than cells [26].

Inverters

Lightning protection of inverters on the ac side can be accomplished by conventional means. Because of the presence of the input capacitors and inductors, it is thought that little transient current will enter the inverter, but that the full transient voltage will stress insulation at the input terminals.

Storage Batteries

There has been little history of lightning transients interacting with batteries because batteries and the associated dc wiring are normally well protected by the building in which they are housed.

Control System

Transients will be induced in the instrumentation and control wiring in the same manner as for the power cables. Protection requirements for the control system are different from those of the power system, because upset rather than catastrophic damage becomes important. Protection strategies include the combination of non-linear terminal protection devices followed by low-pass filters to absorb the considerable high frequency transients generated by the terminal protection devices.

Lightning Protection Techniques

As mentioned earlier, protection from the effects of lightning can be achieved by a combination of three techniques: (a) stroke interception, (b) shielding and (c) terminal protection.

(a). Stroke Interception

Interception is achieved through the use of grounded vertical masts (lightning rods or air terminals), and/or electrical grounded wires. The following topics must be addressed in determining the necessity of stroke interception hardware: personnel safety; the operational effects of a direct hit on the systems; the cost of the interception hardware; replacement cost of damaged elements; and the frequency of direct hits.

(b). Shielding

Shielding provides protection from strikes to earth in the vicinity of the system by reducing the electromagnetic fields which interact with the system conductors. Shielding may be in the form of a conducting shell enclosing a volume, coaxial jackets or conduits through which cables are routed, or buried bare guard wires above cables in a cable trench.

Shielded volumes will be used in photovoltaic power systems when the cost of such protection is small, e.g. grounding a metal building containing storage batteries or sensitive electronic equipment. Cable shields have application in photovoltaic systems for long runs of control and instrumentation cables.

Shielding of the dc power cables by metal conduits or coaxial shields may be prohibitively expensive. An effective and economical alternative is the use of guard or screen wires above cables routed in cable trenches. The presence of a bare conductor, at least 10 in. minimum above the projected cables, in the earth lowers the lightning induced potential in the immediate vicinity to less than 20% of the value with the conductor absent.

(c). Terminal Protection Devices (TPD)

One method of limiting the voltage transients at the terminals of system components is the use of non linear resistors or varistors, and dielectric breakdown devices or sparkgaps. Theses devices are placed in parallel with the terminals to be protected and perform a voltage limiting function by switching from a high impedance to a low impedance.

Non linear Resistors

These devices, generally referred to as varistors, are bipolar devices whose resistance varies with the current through the devices. Varistors perform in a fashion very similar to bipolar junction devices. Their subnanosecond switching speed, wide range of voltages, and large current handling capacity make varistors attractive candidates as transient suppressors.

Dielectric Breakdown Devices

Air gap devices are generally used for lightning protection on power line entrances to user facilities. They have operating voltages up to several hundred kilovolts and can carry large transient currents. Gas filled devices are available for operation at voltages as low as 75 V.

Spark gaps have response times from a few nanoseconds to several microseconds. The voltage reaches a value (determined by the device geometry and pulse risetime) at which the gap is ionized and the impedance switches from a very high to a very low value. After switching, the device voltage drops to a low value termed the arc voltage.

Comparison of TPD Types

For voltages of less than 10V, zener diodes and avalanche suppressors are the only alternatives. Both fail in the short circuit mode. Avalanche devices have superior clamping characteristics because they are designed as transient suppressors.

For voltage applications between 10 and 75V, zeners, avalanche suppressors and varistors are the alternatives. Varistor performance degrades with time and with multiple pulse conditions but zeners and avalanche suppressors retain their characteristics.

For voltages between 75 and 400 volts, gas-filled spark gaps become an added alternative to the three devices mentioned above. Spark gaps have the problem of not extinguishing after operation unless certain circuit design features are incorporated.

Between 400 and 1200V, gas-filled spark gaps and varistors are the alternatives. Varistors are faster in operation but spark gaps can handle more power by virtue of their low arc voltage. Varistor performance degradation has been mentioned before.

For voltages above 1200V, spark gaps are the only alternative.

Ground System Considerations

The design of the ground system is a very important and difficult problem, and is still quite controversial even today.

The earth-electrode system may have many forms including rods driven vertically into the earth, horizontal buried grids of conductors, and water pipes. Mathematical and physical descriptions of several ground systems along with their advantages and disadvantages are available in literature. An important part of the design process for the earth-ground system is the assurance that performance will not degrade over a significant period of time. Procedures that minimize the effects of corrosion and mechanical stress must be used. Material selection and bonding techniques should be carefully considered.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of this report are divided in:

(a). General.
(b). Wind turbines.
(c). Photovoltaic arrays.
(d). Future work.

GENERAL:

1. The occurrence of repeated lightning strikes on objects already protected, especially on tall structures, suggests that there is no such a thing as absolute lightning protection.

2. Any lightning accommodation system is influenced by factors encompassing economics, manufacturing, materials and interference with the environment.

3. The lightning protection system of any wind turbine or photovoltaic arrays is a matter of design. Hence during each phase of the design of a wind turbine, whether it's blades, hub, nacelle, generator, structure, electronics, grounding, shielding, bonding, power distribution, data monitoring and control lines, during fabrication, erection, testing and commissioning, issues regarding the sufficiency or otherwise of the lightning protection scheme would have to be decided, at every step.

4. There is no published data of lightning stroke damages to either wind turbines or photovoltaics. This observation applies to both Canada, and the U.S. (though during the last 2-3 years an effort was under way in the U.S). The same observation applies to the international scene.

5. Due to the lack of data on lightning strikes and damages to wind turbine and photovoltaic generator sites it is impossible to analyze such data and provide recommendations on how to improve the lightning protection of existing facilities.

6. Assuming that such data on lightning strikes and damages to wind turbines and photovoltaic arrays was available, it must be stressed that, the recommendations on improvements of existing facilities would have been of limited scope, simply because lightning protection is a matter of design. If a design has shortcomings, then it must be redesigned and an improved version of the original component or system be manufactured and installed.

7. The effectiveness of any given lightning accommodation system is predicated on the conductivity or lack thereof of the ground where the wind driven turbine or photovoltaic generator structure is built.

8. Grounding grids commensurate with the ground conductivity must be considered early in the design phase of the site.

9. One improvement of lightning protection can be achieved by an improved grounding system. Improvements on grounding can be materialized, by additional ground network or by the use of boreholes and bentonite, especially on dry or rocky terrain. A similar technique using bentonite, is to excavate a radial trench to a depth of 30-50 cm, install bare copper pipes, and braze them together at a common point and cover them with bentonite.

10. Radioactive head lightning protection is still viewed with skepticism and generally treated as a "not proven" technology.

11. The lightning protection effectiveness claimed by the Dissipation Array System (DAS) is impressive. However, there is a lot of skepticism among scientists and engineers about the effectiveness claimed.

12. The "rolling ball" theory explains why structures lower than the lightning rod, do receive on occasions strikes.

WIND TURBINES:

1. The lightning protection afforded to a wind turbine is a compromise of numerous factors, often conflicting, such as safety, manufacturing processes and techniques, qualities of materials used, costs, location, height, isokeraunic levels, ground impedance and type of machine used (vertical axis vs horizontal axis).

2. The ground rules established by Lewis Research Center on the roles of the various factors affecting any lightning accommodation system, i.e. economics, manufacturing, materials and interface with the environment, are significant guidelines on lightning protection of wind turbines.

3. It is very important to incorporate the design of the electrical ground system into the initial design of the tower/ base/ pad/ foundations/ piers/ footing/ rock anchors.

4. The protection of instrumentation and controls is probably the most difficult part of lightning protection, because sensors tend to be very sensitive to high voltage/current surges and experimental turbines tend to have extensive sensor wiring on them.

5. While in most cases there is a very limited selection in the type of sensor one can choose, it is beneficial to realize that some sensors can withstand voltage or current surges better than others.

6. It has been proposed that the application of fiber optic data links, to control communication functions at wind turbines would provide the maximum amount of isolation for electromagnetic and electrostatic interference and damage.

7. The blades on most VAWTs are virtually immune to damage even from a direct hit, since they are normally constructed of extruded aluminum, which is an excellent conductor.

8. Ground gradient voltage can be extremely high reaching 150 kV/m near the turbine, and can be lethal unless measures are taken to reduce the soil resistance and improve the ability of the local area to absorb the lightning charge. Failing the above, the site should be fenced-off and personnel removed from the site during intense storms.

PHOTOVOLTAIC ARRAYS:

1. The probability of a stroke attaching directly to a system conductor is small. The incidence of strokes to earth within 100 meters of the facility is much higher and constitutes the major threat to the system; hence the threat is from coupling of lightning-generated fields to buried and above-ground system conductors.

2. Most of the photovoltaic power plants have small height, usually just a few meters, hence nothing special would be required for lightning protection. A good grounding system would suffice.

3. For taller structures of PV power plants, such as the ARCO plant at LUGO (1MW), again, lightning hardening to the structure and a good grounding would suffice. In fact, in the literature reviewed no mention is made about lightning, which could lead to a conclusion that the lightning threat is rather minimal, in such cases.

4. Almost all of the PV systems lightning protection have bypass and blocking diodes.

5. The interior electronics of power conditioning units (PCU) is generally not vulnerable to high frequency transients on the d.c. side because of the RC filter at the input of the PCU.

6. For PV systems the cost of terminal protection hardware such as varistors, spark gaps, and semiconductor devices is very small. The cost of shields and guard wires is small but significant. The cost of direct stroke protection is large and site dependent.

7. The optical flash from lightning does not present a significant threat to cells of flat plate or concentrator systems of photovoltaics.

8. Protection requirements for the control system of photovoltaic arrays are different from those of the power system, because upset rather than catastrophic damage becomes important.

FUTURE WORK:

1. Compile information about lightning stroke incidents and pertinent damages at wind turbine and photovoltaic arrays sites, in Canada. This assignment could be: preparation and mailing of a typical form of questionnaire, compilation of replies into statistical data, analysis of this data, enhance findings by visit(s) to the sites that have experienced repeated lightning strikes or suffered major damages. Conclusions.

2. Review information about lightning stroke incidents and pertinent damages at wind turbine and photovoltaic arrays sites in the U.S. A compilation project is under way by the Lightning Research Laboratory of Southern Illinois University. Analyze findings and look for similarities with Canadian experience. Conclusions.

3. Some questions were raised in the past about the sufficiency of the CSA standard on lightning protection of wind turbine and photovoltaic generator sites. This could be reviewed against current state of knowledge. Recommendations.

4. Further study on the Dissipation Array system could be undertaken in the future, firstly, to

verify the effectiveness claimed, and secondly, to investigate its application to wind turbines and photovoltaic systems. Conclusions and recommendations.

6.0 LIST OF FIGURES

Figure 1 Current Waveform components

Figure 2 Model of lightning current

Figure 3 Canada Annual Thunderstorm Days

Figure 4 Rolling Ball Theory of Stroke

Figure 5 Mechanism of Protection Cone Failure

Figure 6 Lightning Protection Zone in the Catenary Wire System, to protect a tall launcher

Figure 7 Dissipation Array System Concept

Figure 8 Electrical Power Protection

Figure 9 Generator Lightning Hazards

Figure 10 Synchronous Generator Protection

Figure 11 Fundamental protection system for generators

Figure 12 Penetrating conductors into shields

Figure 13 Damage to Electronics

Figure 14 Nested Barriers

Figure 15 Ground System Consisting of Reinforcing Bars, Rings and Counterpoises

Figure 16 Step and Touch Potentials and Sideflash

Figure 17 Grounding Topology

Figure 18 Elements of a Typical closed Electromagnetic Barrier

Figure 19 Typical Grounding Anomalies encountered in Practice and some correct alternatives

Figure 20 Completing a Practical Barrier

Figure 21 Path of Lightning Current

Figure 22 Ground Potential kills a cow

Figure 23 Grounding System for Aquilo site

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